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FACTORS AFFECTING SHOCK WAVE NOISE

OF SUPERSONIC AIRCRAFT

by Harvey H. Hubbard [1959] 12p refs

60r1448 Langley Research Center, Langley Station, Va.

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FACTORS AFFECTING SHOCK WAVE NOISE OF SUPERSONIC AIRCRAFT

INTRODUCTION

The shock waves generated by aircraft in supersonic flight may be the sources of objectionable noises at ground level. These noises, which are explosive in character, are now normally called "sonic booms". The objectives of this paper are to describe the nature of the sonic boom, to indicate the factors which affect it, and to briefly mention some of its effects.

The nature of the problem is illustrated in figure 1 for the case of an aircraft in steady level supersonic flight (ref. 1). Two shock waves are usually present. These are referred to as the bow wave and the tail wave. As the generating aircraft flies by, these shock waves can extend to the ground and will sweep by an observer on the ground. The result will be a momentary change in the atmospheric pressure Δp, at the position of the observer as each wave passes. The ear is sensitive to each of these rapid changes in pressure but is insensitive to the slowly varying pressure in between. A microphone having a response similar to that of the human ear senses a pressure time history as shown in the trace at the bottom of the figure. The large peak responses correspond to the rapid pressure changes and are each interpreted as an explosive sound.

METHOD OF CALCULATION

A method is available for estimating the Δp values for various operating conditions, and a convenient form for this expression for engineering use is given in figure 2. This equation, which is taken from the work of references 2 - 5, indicates that the magnitude of Δp depends upon the ground reflection factor which may vary between 1 and 2, the equivalent body shape factor of the aircraft which may vary between approximately .55 and .8, the airplane altitude which involves both distance and pressure gradient, airplane Mach number, airplane fineness ratio, and airplane length. For any given airplane the length, fineness ratio, and body shape constant are fixed and the ground pressures are then a function of the ground reflection constant, the airplane altitude, and the airplane Mach number. The equation just discussed does not account for other variables such as the wind direction and velocity, the temperature gradient, the airplane lift and flight path, and atmospheric losses. For certain conditions, as will be indicated later, some of these factors may significantly affect the Δp values.

FACTORS AFFECTING THE GROUND PRESSURES

As previously indicated, the altitude has a two-fold effect on the magnitude of the ground pressures. The opportunity is taken in figure 3 to compare the calculated Δp values as a function of altitude with some preliminary experimental data for fighter-type airplanes and for the Mach number range 1.2 to 2 (refs. 6 and 7). It can be seen that the calculated pressures drop off rapidly with increasing altitude, whereas the Mach number effects are relatively small for the range of Mach numbers shown. The experimental values have some scatter due, at least in part, to atmospheric effects; however, the general trend of the data with altitude is very similar to that predicted by the theory.

trace. This latter trace also exhibits a longer period and has a different shape. As a result of these tests it was found that the observers associated a sharp crack, as in the case of close-by thunder, with the more rapid rise time, whereas the noise associated with the rounded-off pressure pulses was likened to that of distant rolling-type thunder. This latter phenomenon was noted to be much less objectionable.

Since, in airplane operations at supersonic speeds, the low altitude portion of the flight is the critical one, and because weather conditions can be significant, attention is called to the manner in which some of the atmospheric effects enter into the problem. Some of these phenomena are illustrated in figure 5, in which is shown the effect of the normal temperature gradient on shock wave propagation. Schematically shown are two airplanes in steady flight at Mach numbers of 1.1 and 2. For simplicity only the bow shock wave is considered. At a Mach number of 1.1, the bow wave does not extend all the way to the ground. If the temperature was constant at all points between the airplane and the ground, the bow wave would take the position of the dashed line and would intersect the ground. There is usually a temperature gradient present, the ambient temperature at ground level being higher than at altitude. This temperature gradient affects the shape of the wave because the lower extremèties propagate faster than the upper extremeties, thus resulting in a bending forward of the wave as shown. This temperature effect is beneficial since, in some cases at low supersonic Mach numbers, it causes the wave to miss the ground completely.

In the second illustration of the figure where the local airplane Mach number is 2, the speed of the airplane exceeds the speed of sound at

So far we have only considered the observer on or near the flight track. For practical considerations, it is also of interest to know the extent to which the boom extends outward from the track. Some insight into this phenomenon is given in figure 4, in which both calculated and experimental data are again given for a fighter-type airplane at an altitude of 35,000 feet (ref. 6). The pressures are shown as a function of lateral distance from the track in miles. The calculated curve indicates a maximum pressure along the flight track, a decreasing pressure with increasing lateral distance, and a sudden cut-off due to refraction effects. These refraction effects arise because the air near the ground is at a higher temperature than the air at altitude, resulting in a more rapid propagation of the waves near the ground. The experimental data confirm, in general, the trends predicted by the theory and, in particular, the extent to which the boom extends laterally.

Also of interest are the reactions of observers during the tests for which the above data were obtained. Somewhat different reactions were observed at distances of 4 and 10 miles, respectively, even though the Δp values as indicated in the figure were not markedly different. This difference in the reaction may be tied in with qualitative differences in the pressure time histories, as illustrated in the sketches of the figure. The pressure trace obtained close to the track exhibited a rather rapid rise time, whereas the pressure trace recorded at a distance 10 miles off the track exhibited a rounded-off appearance as indicated by the lower ground level and the wave thus reaches the ground despite its curving due to temperature gradient. Wind gradients will have similar effects of wave propagation and may either increase or decrease the curvature of the wave. Some beneficial combinations of wind and temperature gradients may make it possible to operate up to Mach number 1.4 in level flight at high altitudes without having the shock waves reach the ground. If it were possible, however, to climb at sufficiently steep angles, the shock waves might miss the ground for Mach numbers somewhat higher than 1.4.

STRUCTURAL DAMAGE

For all flight Mach numbers at relatively low altitudes, there is a possibility of doing some physical damage. There have been numerous claims of damage from sonic booms but very few well documented cases where damage was correlated with the conditions of the flight. This opportunity is taken to cite one example where damage to a large plate glass store front window was correlated closely in time with the passage of a fighter-type airplane (ref. 6). The orientation of the building relative to the radar track of the flight and the nature of the resulting damage are shown by the schematic diagrams of figure 6. It was noted that the airplane passed essentially over the building and the reported time of the damage correlated closely with the flight time. Although ground noise pressures were not measured at the site of the reported damage, they were estimated to be somewhat in excess of 1.75 lbs per sq. ft. measured at a distance of four miles off the track.

The radar track direction, the flight Mach number, and the orientation of the building were such that the shock waves impinged essentially normal to the window surface. The sketch of damage in the insert indicates that the 120" by 90" center window panel which was firmly supported at the top and bottom had a crack extending almost horizontally across the width. No damage was noted to the two adjacent panels of glass. The fact that similar windows on either side of the cracked window did not break would imply that the ground pressures incurred in this test, estimated to be about 2 lbs per sq. ft., are near the magnitude where damage might begin to occur for large commercially-installed plate glass windows.

CONCLUDING REMARKS

In summary, it has been noted that the ground noise pressures associated with the shock waves of the supersonic aircraft may be objectionable to people on the ground and, in the extreme cases, may cause physical damage to light structures. For some particular atmospheric conditions and for low Mach number operations, there may be no noise disturbances on the ground due to the shock waves of the airplane. At higher Mach numbers where ground disturbances cannot be avoided, the intensity of the noise is noted to be largely a function of the altitude and lateral distance of the aircraft. Thus, the manner in which the aircraft is operated is an important factor in minimizing the shock wave noise pressures at the ground.

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~~[illegible]~~

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NATURE OF THE PROBLEM

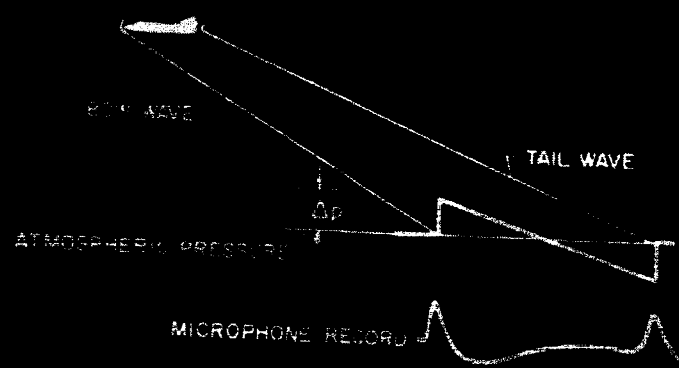

FIGURE 1

EXPRESSION FOR GROUND PRESSURES

$$\Delta p = K_1 K_2 \left(\frac{\sqrt{p_a p_o}}{y^{\frac{3}{4}}} \right) (M^2-1)^{\frac{1}{8}} \left(\frac{1}{\frac{l}{d}} \right) l^{\frac{3}{4}}$$

WHERE

K_1	GROUND-REFLECTION CONSTANT
K_2	BODY-SHAPE CONSTANT
p_a	AMBIENT PRESSURE AT ALTITUDE
p_o	AMBIENT PRESSURE AT GROUND LEVEL
M	AIRPLANE MACH NUMBER
l/d	BODY FINENESS RATIO
l	BODY LENGTH
y	DISTANCE NORMAL TO FLIGHT PATH

FIGURE 2

PRESSURES ON GROUND ALONG TRACK
FOR FIGHTER TYPE AIRPLANES

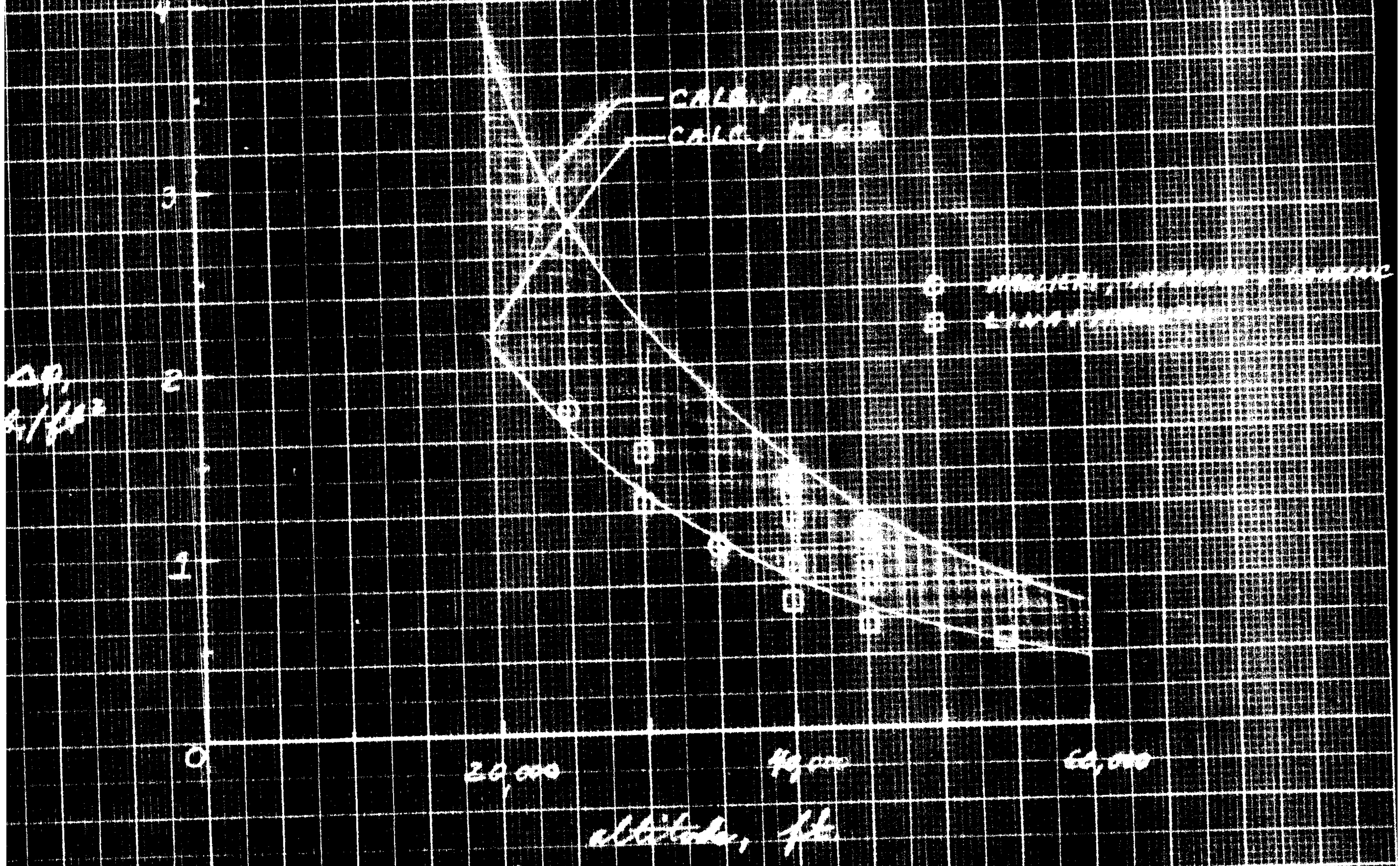

FIGURE 3

EFFECT OF DISTANCE FROM FLIGHT TRACK
M = 1.3 , ALTITUDE = 35,000 FT.

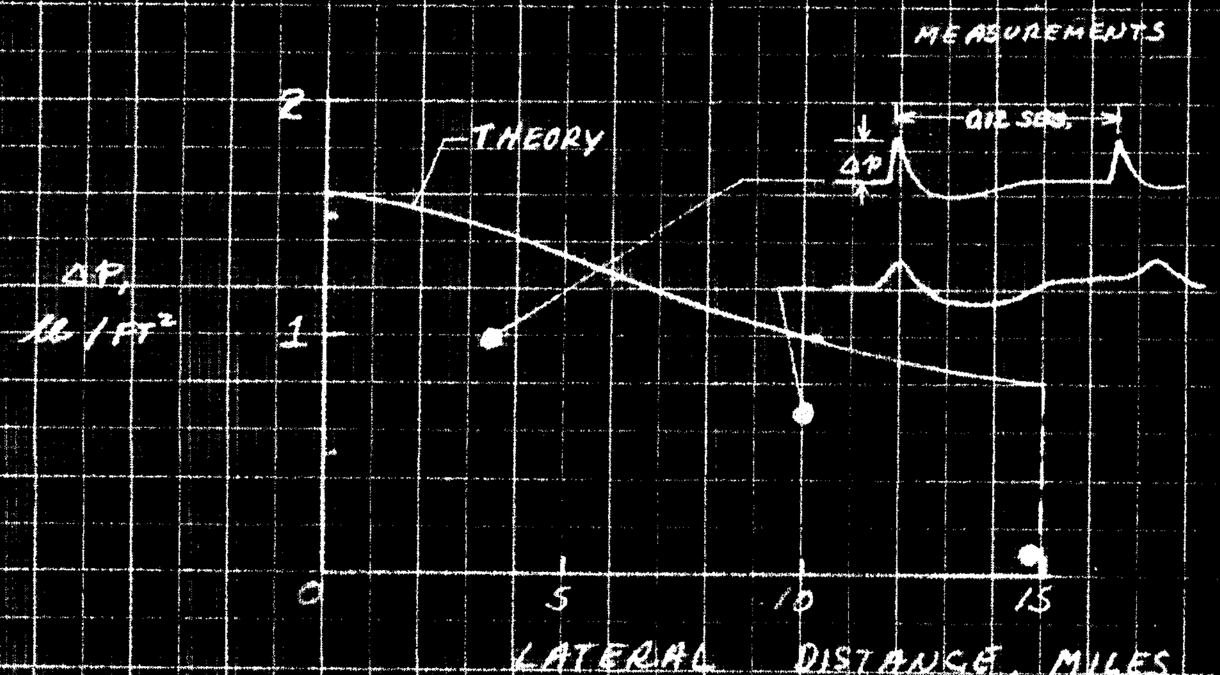

FIGURE 4

EFFECT OF TEMPERATURE GRADIENT
ON BOW-WAVE PROPAGATION

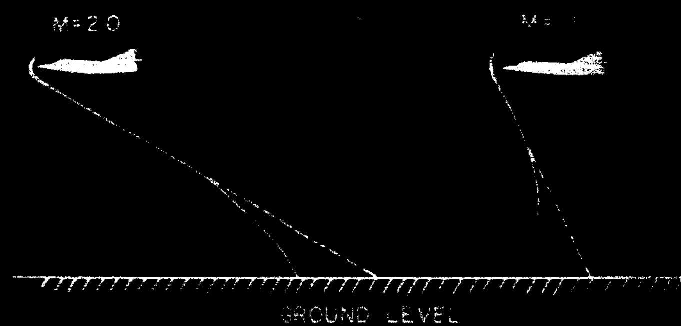

FIGURE 5

[illegible] DAMAGE TO [illegible]

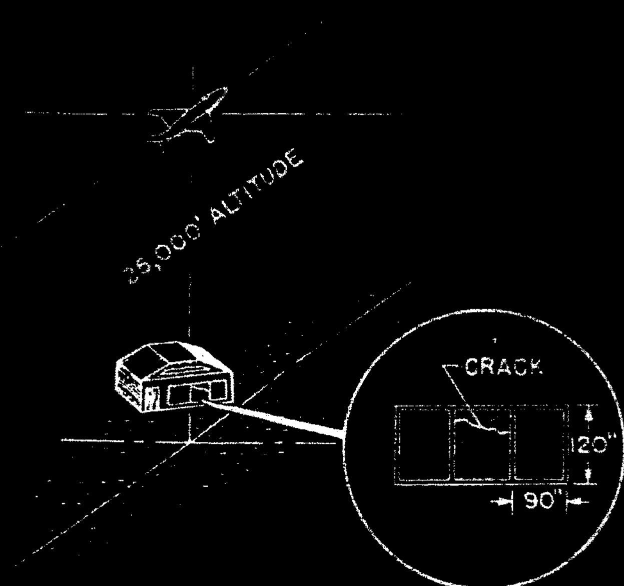

FIGURE 6